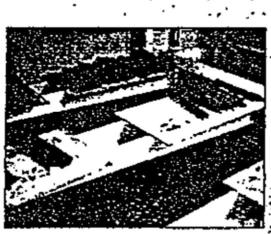


The cost of infrastructure needs

A USEPA survey of drinking water infrastructure needs yields data used to construct cost models for more than 50 types of water supply projects.

Patricia Carroll Hertzler and Clive Davies

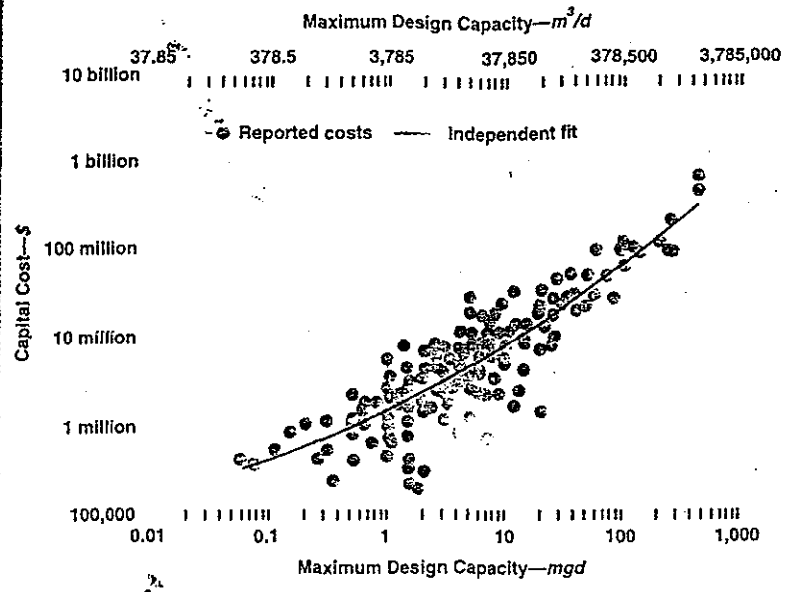
A survey conducted by the US Environmental Protection Agency provided a wealth of information on the cost of drinking water infrastructure needs. This information was used to develop cost models for more than 50 types of source, treatment, storage, and transmission and distribution projects. The cost models provide the tools to accurately estimate the total infrastructure investment needed by community water systems in the United States. They also give insight into real-world costs for common types of drinking water infrastructure projects.

Recently the US Environmental Protection Agency (USEPA) completed* the first nationwide survey documenting community water systems' infrastructure needs.[1] The survey shows that water systems nationwide must invest $138.4 billion over the next 20 years. Of this total, $12.1 billion is needed now to meet current Safe Drinking Water Act (SDWA) requirements. No prior survey had comprehensively examined the needs of water systems across the United States. USEPA conducted this survey to provide local, state, and national policy-makers with comprehensive information on the condition of drinking water infrastructure nationwide.

The drinking water infrastructure needs survey represents an important step in carrying out

*With contractor support from The Cadmus Group Inc., Waltham, Mass.

FIGURE 1 Estimated capital cost of filtration as a function of maximum design capacity



R^2—log = 0.76; number of observations = 234

TABLE 1 Reported needs for selected types of treatment

Type of Treatment	Number of Projects Reported*
New or rebuilt filtration plants (e.g., conventional, direct, and slow sand)	479
Aeration (for volatile organic compounds or iron)	136
Granular activated carbon (as an added unit process)	81
Reverse osmosis (for currently regulated contaminants)	80
Lime softening	54
Ion exchange	51

*Includes projects with and without cost estimates

the 1996 amendments to the SDWA. The reauthorized SDWA includes provisions for a drinking water state revolving loan fund (SRLF). The drinking water SRLF will provide grants to states, which could, in turn, make low-interest loans to public water systems. Federal money would be combined with state matching funds. The results of the drinking water infrastructure needs survey conducted by USEPA indicate the magnitude of the need and, under the law, provide the basis for allocating drinking water SRLF money among states.

Four thousand community water systems participated in the needs survey. The survey sampled each of the nation's 794 large systems (serving 50,000 or more people) and included random samples of 2,760 medium systems (serving 3,301–50,000 people) and 537 small systems (serving 3,300 or fewer people). In addition, the needs of 77 Native American systems were assessed. Overall, 94 percent of systems responded, including all but 10 large systems.

Many of the participating drinking water systems provided capital improvement plans or engineering reports that documented the estimated cost of their infrastructure needs. However, about half of the more than 35,000 needs reported lacked documented cost estimates. More than 50 models were developed to assign costs to these projects.[2] This article describes these models and provides five examples of specific models.

Information collected project by project

The needs survey questionnaire collected information on a project-by-project basis. Water systems reported the type of project (e.g., an elevated storage tank), a limited number of design parameters (e.g., capacity), and the estimated cost, if available. To minimize the time required to complete the questionnaire, information on only the most important design parameters was solicited.

Projects varied widely in scale and purpose. For example, the two largest utilities serving the greater Los Angeles, Calif., area documented more than 100 needs, including a direct filtration plant, three large raw water storage reservoirs, and the replacement of miles of distribution line. On the other hand, Fritz's Mobile Home Estates, which serves 33 people in Amsterdam, N.Y., reported needs for a new well house, a new well pump, elimination of a well pit, and installation of a hydropneumatic storage tank.

Models assigned costs to needs

The objective of the modeling effort was to assign the most accurate costs to documented needs that lacked cost estimates. Accuracy was important because costs assigned using the models were combined with reported costs before extrapolation to estimate the total need of all community water systems. From a statistical standpoint, the best data source for constructing models to estimate these missing costs was cost data reported by other systems that participated in the survey.

Some models relied on project design parameters to calculate costs, whereas others estimated costs as a function of population served. For example, the model for elevated storage yields cost as a function of capacity; it is based on the estimated cost of constructing elevated storage tanks as reported by survey participants. Needs survey cost models were developed to estimate the costs of more than 50 types of infrastructure needs.

PHOTO: DAVE SCHULTZ

Eighty percent of the survey respondents identified transmission and distribution needs (left), and filtration was identified as the largest single treatment need (right).

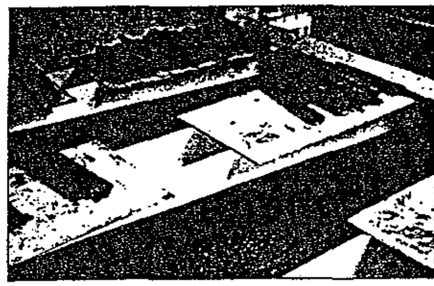


PHOTO: WISCONSIN DER

*Although data limitations did not allow the cost mod*els to be tailored for every level of construction (e.g., new construction, full replacement, partial replacement), the models did differentiate between comprehensive construction projects and refurbishment projects.

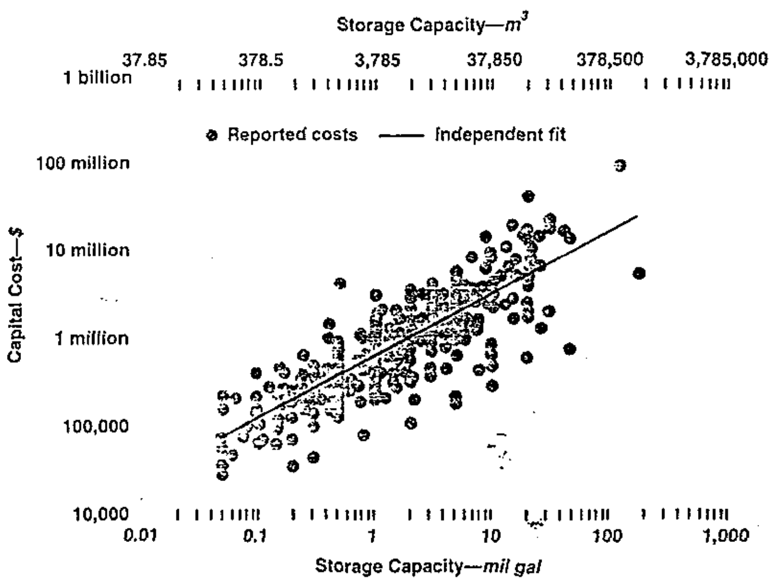
Data used to construct models had to be representative of the types of projects being modeled. That *meant, for example, investigating outliers and exclud*ing them as appropriate. To reflect regional variations in construction costs, reported costs were adjusted using location factors published by the R.S. Means Company.[3] Also, costs were escalated or de-escalated to January 1995 dollars using the Construction Cost Index.[4]

When *infrastructure costs* were a continuous function of the design parameter that served as the independent variable, models relied on linear regression to plot a cost curve. This was the case for most types of infrastructure projects. But for some types of infrastructure, such as water mains, cost is generally estimated in unit quantities (e.g., dollars per metre or foot). The costs of distribution mains of given diameters, for example, are generally estimated based on the length needed. Unit costs for these types of infrastructure were plotted on bar graphs.

Examples of models based on linear regression

The classical linear regression technique was used in most of the needs survey cost models. This technique estimates the linear relationship between a desired output (dependent) variable, such as capital cost, and known input (independent, or explanatory) variables, *such as maximum design capacity. By using this lin*ear regression technique, an assumption is made that the dependent variable is a linear function of the independent (explanatory) variable. The needs survey methodology compensated for some of the weaknesses in the linearity assumption as it relates to drinking water infrastructure. Linear regression was applied *to the logarithms of the input and output variables.* This log–linear regression provided a good fit to data that vary by several orders of magnitude. The following sections offer examples of needs survey cost models based on log–linear regression.

FIGURE 2 **Estimated capital cost of ground-level finished water storage as a function of capacity**



R^2—log = 0.70; number of observations = 521

FIGURE 3 Estimated capital cost of elevated storage as a function of capacity

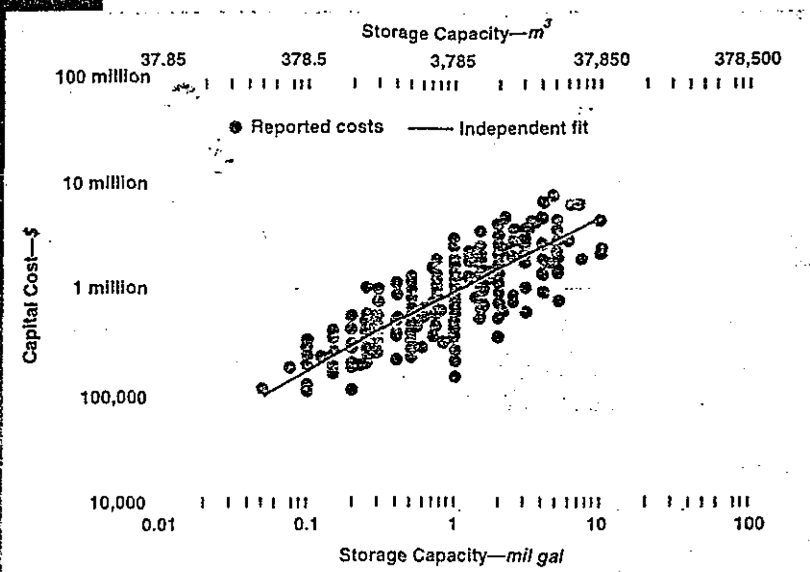
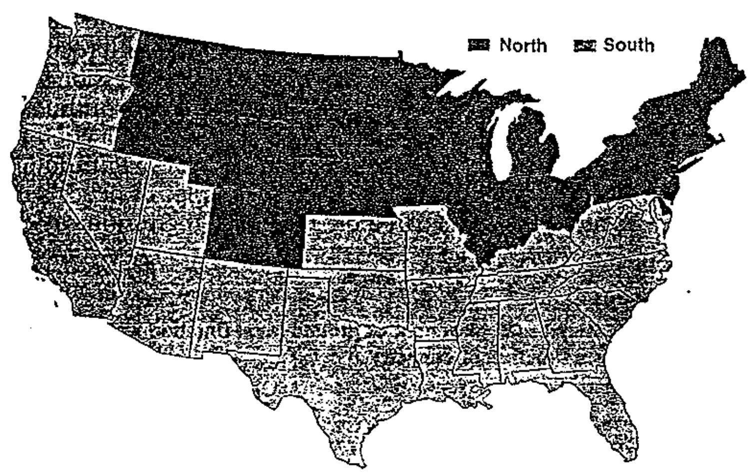


FIGURE 4 Geographic areas used for distribution and transmission cost models



Filtration the largest single treatment need. Twenty percent of the systems using surface water reported a need to install or replace filtration plants now or over the next 20 years. As shown in Table 1, filtration is the largest single treatment need. For this reason, the quality of the filtration cost model was very important in estimating total need.

Figure 1 shows the cost model for filtration. The model was based on cost estimates provided for 234 new and replacement filtration plants across the United States. Capacities ranged from less than 230 m^3/d (0.06 mgd) to 1.7×10^6 m^3/d (450 mgd). Costs to install a filtration plant were as high as $500 million.

The filtration model estimates cost as a function of maximum design capacity. It uses data for various filtration technologies, including conventional, direct, diatomaceous earth, and slow sand filtration. Eighty-five percent of the cost observations were for conventional filtration, which has the most influence on the curve. When the cost of filtration technologies other than conventional filtration were plotted, the resulting curve was similar to that in Figure 1. The curve based on the combined results was chosen because it produced the best fit. It appears that site-specific factors accounted for a greater portion of the cost variability than did the type of filtration technology.

The data used to generate the filtration cost curve yielded an R^2 of 0.76, a very good fit for a single-variable model. An R^2 of 0.76 means that about 76 percent of the variation in cost is explained by the independent variable (in this case, maximum design capacity). The cost estimates produced by this model are within 2 percent of the costs from the filtration cost model developed independently through the regulatory-negotiation process that resulted in the proposed Disinfectants/Disinfection By-products (D/DBP) Rule. The model developed through the regulatory-negotiation process reflects costs to install conventional filtration for turbidity and *Giardia* removal.

More than one fourth reported a need for storage facilities. More than 25 percent of water systems surveyed reported a need for new finished water storage facilities, and the needs survey estimates a 20-year storage need of $12.1 billion. Two models for new finished water storage tanks were necessary because of the significant cost difference between ground-level and elevated storage. Figure 2 shows the cost curve for ground-level finished water storage, and Figure 3 shows the curve for elevated storage. The models produce cost estimates as a function of storage capacity. A separate model not discussed here was used to estimate costs for installation of hydropneumatic storage.

The cost model for ground-level storage was based on 521 estimates, and the model for elevated storage was based on 476. It was no surprise that most of

More than 25 percent of the survey respondents identified a need for new finished water storage facilities, and the survey estimates a 20-year storage need of $12.1 billion.

the estimates were for common tank sizes. On the cost curve for elevated storage, for example, 101 of the 476 estimates were for 3,800-m^3 (1-mil gal) storage tanks. Because most of these estimates were clustered around $1 million, many of them are hidden. Only a handful of outliers are visible as discrete observations. The same is true of other standard tank sizes.

Although most observations were clustered around the models' predicted value, the models show significant variability for particular tank sizes. The costs of 3,800-m^3 (1-mil gal) ground-level storage tanks, for example, vary by almost an order of magnitude. This is probably due to a number of factors, such as land values, environmental concerns, site-specific conditions, construction materials, and required appurtenances. Despite this variability, the R^2 of each is about 0.7.

Examples of models based on average costs

For some types of projects, infrastructure is priced in unit quantities. Distribution and transmission mains, water meters, and backflow prevention devices are examples of equipment that is usually priced and purchased per unit. Cost models for these types of projects were based on average costs. The models were developed by applying location factors to cost observations and averaging the adjusted cost observations within a particular equipment size category. For example, the cost estimate for 51-mm (2-in.) water meters was developed by averaging the adjusted cost estimates for 51-mm (2-in.) water meters submitted on the survey questionnaires.

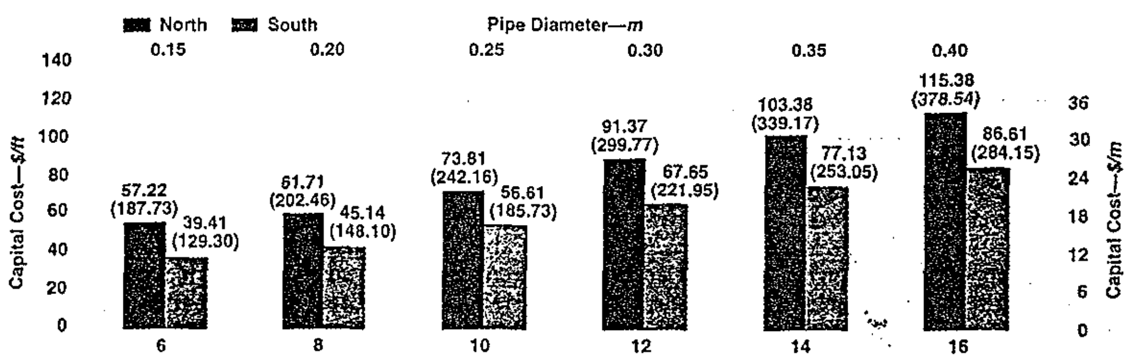
Transmission and distribution is the largest category of need. Eighty percent of the respondents reported transmission or distribution needs for a total 20-year need of $77.2 billion.

Many factors influence the costs of water mains. These factors include pipe transportation costs, weather conditions affecting construction, pipe length and diameter, pipe materials, pressure rating, depth at which pipes are buried, soil type, traffic, urban versus rural location, and environmental concerns. To minimize the burden on respondents, however, the survey questionnaire collected information only on the factors that most affect transmission and distribution costs.

Survey respondents were asked to provide pipe length and diameter information and to indicate whether needs were for transmission or distribution. These parameters served as inputs to the models.

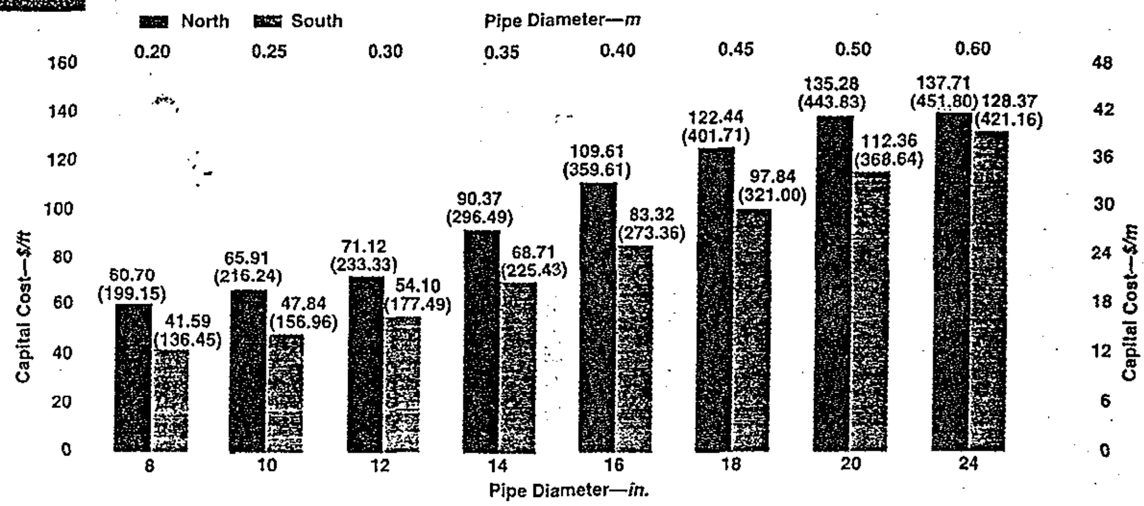
The models also considered the geographic area in which the water system is located. Geographic area was an important determinant of cost because it served as a surrogate for weather conditions that

FIGURE 5 Estimated capital cost of distribution mains as a function of diameter and geographic region



Numbers above the bars indicate dollars per foot, followed by dollars per metre in parentheses

FIGURE 6 **Estimated capital cost of transmission mains as a function of diameter and geographic region**



favor construction in the southern United States, the depth at which pipe is buried, and other factors that vary by geographic area. Frost depth data[3] served as a basis for defining the geographic areas, because weather conditions and the depth at which pipes are buried are closely related to frost depth. Northern states are characterized by a maximum penetrable frost depth of greater than the national median of 0.9 m (36 in.), and southern states have a maximum penetrable frost depth of less than 0.9 m (36 in.). Figure 4 shows the northern and southern geographic areas to which states were assigned.

Figure 5 shows unit costs for distribution mains up to 0.4 m (16 in.) in diameter, and Figure 6 shows unit costs for transmission mains up to 0.6 m (24 in.) in diameter. These models estimate cost per metre (or linear foot). The costs reflect the average cost per metre (or foot) reported by diameter, pipe type (transmission or distribution), and geographic region (North or South).

Cost differences between transmission and distribution decreased as the pipe diameter increased. Therefore, transmission and distribution costs were combined in the same model for pipe diameters between 0.5 and 0.6 m (18 and 24 in.) and are shown as part of Figure 6. The authors speculate that the costs begin to converge at larger diameters because trenching and pipe costs affect cost more significantly than do costs of appurtenances.

As Figures 5 and 6 show, transmission and distribution costs were consistently lower in the South, even after adjusting the indexes for observations based on location. (Without this adjustment, the differences would be even more dramatic.) The variance of cost data reported by respondents was generally lower when the North and South were examined individually, rather than combined. This implied that geographic region was a key determinant of cost. The authors speculate that this difference is largely due to differences in weather conditions affecting construction, the depth at which pipe must be buried, urban versus rural location, and other site-specific conditions. Because most ductile-iron pipe is manufactured in the South, pipe transportation costs would also be lower in this region.

For pipe diameters larger than 0.6 m (24 in.), cost variations based on geographic area become less significant. The needs survey model for larger main sizes used one unit cost for each pipe size, regardless of whether the piping was for transmission or distribution or was located in the North or South. Although the data do not allow for definitive conclusions, it is likely that trenching costs do not increase as significantly as pipe costs as diameters become larger.

Construction of large-diameter mains is often very expensive. Therefore, the costs associated with pipes measuring 1.2 m (48 in.) in diameter or greater were important because of their effect on estimates of total need. Because the needs survey did not yield enough data to build cost models for these pipe sizes, these costs were estimated on a case-by-case basis.

In preparing cost estimates, contractor staff contacted all systems that reported needs (but no cost estimates) for 1.2-m (48-in.) or larger piping. If a system had either prepared a cost estimate or completed the construction project since submitting its questionnaire, the new cost data were used. If the system did not have actual costs or documented estimates, as much information as possible was gathered about the project. Experts in water supply design and construction and experts from the water system reporting the need or the engineering firm doing the design work were consulted. Advice from all parties was used to establish an acceptable range of construction costs for each project. Based on best professional judgment, cost estimates were then assigned to each project.

Applying the cost models

Models were used to estimate the costs of reported projects that lacked an associated cost estimate. The methodology used to apply the cost curves was straightforward.

- For the design parameters reported for projects without cost estimates, USEPA determined the cost predicted by the needs survey cost model for an average water system. For example, the filtration model (Figure 1) predicts a cost of about $1.8 million for a 3,800-$m^3$/d (1-mgd) plant.
- To account for regional variability in construction costs, the average predicted cost was adjusted using the location factors described earlier. The adjustment would increase the cost in regions where construction costs are typically higher than average and decrease the cost in regions where they are typically lower.

The model applied for water mains depended on whether a system was in the North or South and on whether the system reported needs for transmission or distribution. The reported and modeled costs for the statistical sample of systems were extrapolated to the population of all community water systems to derive the total US infrastructure need.

Limitations

Although the cost data gathered in this first-time survey of drinking water systems' infrastructure needs allowed USEPA to estimate total nationwide needs, the needs survey took into account only a limited number of the factors that influence the cost of infrastructure. The survey relied on the voluntary (and much appreciated) participation of approximately 4,000 water system owners and operators across the United States. Although data on factors such as materials type or depth of pipe burial would have allowed USEPA to construct more complex (and more accurate) models, the agency chose to limit the types of design parameters for which information was gathered in order to minimize the burden on water system professionals participating in the survey. USEPA also recognized that systems that have a documented need, but not a cost estimate, may not have enough information on design parameters to justify more complex models. The parameters included were reviewed by a consulting engineer with many years' experience modeling the design and construction costs of drinking water system infrastructure. Nevertheless, although the cost curves presented in this article are useful and appropriate for the development of nationwide estimates, they are not appropriate for detailed budgeting of individual projects.

Conclusions

The simple cost models developed for the drinking water infrastructure needs survey generally provided good results, especially for the most widely needed types of infrastructure projects.

- Survey respondents reported filtration costs that mirror those estimated through the regulatory-negotiation process that resulted in the proposed D/DBP Rule. Reported filtration costs depended largely on design capacity, with an R^2 of 0.76. Although data on filtration other than conventional filtration were somewhat limited, the costs that were reported showed that the type of filtration affected costs less than the authors had expected.
- As expected, the costs of ground-level and elevated storage depended largely on storage capacity. The R^2 of each was about 0.7. Although a large majority of reported costs were close to the US average, costs for a given tank size varied by almost an order of magnitude because of site-specific conditions.
- Reported costs of transmission and distribution were consistently higher for systems in the North than for systems in the South. The authors believe that this is largely due to differences in weather conditions affecting construction, the depth at which pipe must be buried, and other factors such as urban versus rural locations and other site-specific conditions. Distance from major manufacturers also influences construction costs.

In spite of the constraints on design parameters, the authors were able to develop cost models to meet USEPA's primary objective—to assign the most accurate costs possible for all documented needs in the statistical survey so that needs could be accurately extrapolated to all community water systems. Survey results, which were released in January 1997, will provide Congress, the states, and the water industry with valuable information on drinking water infrastructure needs.

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